Use of Lime-iron Sludge for Soil Modification

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Abstract

The worldwide increase in production of water treatment sludge together with the overwhelming disposal cost has fuelled research into the development of economic re-use alternatives. This study investigated the shear behaviour of unmodified and modified clay to determine the potential of using lime-iron sludge as a soil modifier. The effects of lime-iron sludge concentration, moisture content and vertical normal stresses were examined.

The optimum dose of lime-iron sludge was found to be 3% with an accompanying optimum moisture content of 20%. An improvement of 20% increase in shear stress together with a rise in cohesion of 155% was observed. However, the inclusion of lime-iron sludge in soil specimens had no significant effect on the internal friction angle.

Experimental results were successfully used to illustrate the positive effect of lime-iron sludge inclusion on the shear behaviour of soil. Additionally, experimental data was successful in correlating shear variables and optimizing soil parameters to aid in the eventual development of full-scale design.

Keywords

Modified; Lime-iron Sludge; Direct Shear Test; Shear Stress; Peak Stress; Residual Stress; Inorganic Clay

Introduction

Increasing quantities of Water Treatment Sludge (WTS) are being produced worldwide due to increased water demand, more stringent controls over the quality of produced water and lack of suitable reuse for residuals.

WTS often defines the residual produced from water softening, chemical coagulation, flocculation, and settling processes used in the treatment of potable water (Twort *et al.* 2000). Added coagulants cause the impurities to aggregate into flocs that can be separated from the water, removing not only the impurities but also the chemical additives.

A popular approach to WTS disposal is to discharge into an excavated lagoon where it is left indefinitely. This is not a long-term solution as lagoons have a finite capacity and landfills occupy significant land space. Further, such solutions are a major financial burden to the water treatment plant due to cost of drying, loading, and transporting the sludge.

According to Moldan (1990) most environmental protection regulations require that the quantity of waste produced is minimized. If possible, the wastes should be re-used or processed as secondary raw materials as much as possible. Otherwise, the solid wastes should be put back in the environment where the space occupied should be as little as possible and minimum costs should be achieved.

Reported methods of soil modification include physical processes such as soil densification, blends with other material, use of reinforcements (Geogrids), and chemical processes such as mixing with cement, bituminous emulsions, fly ash, lime, lime by-products and blends of any one of these materials. (Soil Stabilization in Pavement Structures, 1979). Improved soil properties such as strength, plasticity, compressibility, deformation, hydraulic conductivity, workability, durability, swelling potential, and volume change tendencies have been reported.

Water treatment sludge may be classified as either lime sludge or lime-iron sludge. According to Benešová (2004), the typical average iron content of iron sludge is 19.5% while the typical average iron content of lime sludge is 1.88%. While numerous studies have been reported in the literature on the reuse of lime-sludge as a soil modifier, little has been reported on lime-iron sludge. Yu, Zhang and Cartweight (2010) conducted a pilot investigation on the beneficial utilization of lime-sludge for subgrade stabilization. The results of the investigation indicated little improvement in unconfined soil strength.

However the modification demonstrated positive effects in reducing the plasticity of soil and increasing its durability and deformation.

Watt and Angelbeck (1977), in a study of the effects of adding lime-sludge to a road sub-base aggregate, found that addition of 0.5 to 1.0% sludge produced maximum improvement to the seven-day cure and freeze/thaw unconfined compressive strengths. The mix design was 86% aggregate, 11% fly ash, 3% lime, and 0 to 3% sludge solids.

According to Baker et al. (2005) the use of lime-sludge as a soil modifier holds promises from both performance and economic aspects. The large amount of sludge available and the fact that it is inexpensive (essentially free) is very attractive if it can be used for soil modification in transportation constructions.

In this investigation the effect of lime-iron sludge as a soil modifier is reported. The characteristics of lime-iron sludge are determined using the Atterburg's limits, and direct shear testing. Experimental data was analysed in an attempt to explicate the correlation of shear variables and determine the optimum parameters to aid in the eventual development of full-scale design.

Test Program

Materials Used for Testing

Experimental studies were carried out using lime-iron sludge obtained from a water treatment plant located in central Trinidad. The material, which is not currently re-used, was produced from water treatment processes used for the removal of iron from ground water. Lime-iron sludge specimens were subsequently classified as inorganic silt of low plasticity according to the Unified Soil Classification System. This lime-iron sludge was tested as a modifier using a soil obtained from the Northern Range of Trinidad. The soil was classified as inorganic clay of medium plasticity according to the Unified Soil Classification System.

Methodology

This study examined the shear behaviour of unmodified and modified soil specimens. The main variables considered in the tests are as follows:

- Lime-iron sludge concentration
- Moisture content
- Vertical normal stress

Samples of soil and/or lime-iron sludge were classified using the multipoint liquid limit method of the Standard Test Methods (ASTM D4318).

The Standard Test Method for Direct Shear Test of Soils under Consolidated Shear Condition, (ASTM D3080) was performed using a direct shear machine (ELE International T206) to characterize the shear parameters presented in this paper. The tests were conducted in a shear box 5.0 cm by 5.0 cm in plane and 4.2 cm in depth. The shearing rate was 0.001 cm/s. Shear stresses were recorded up to a horizontal displacement of 1.2 cm in order to observe the post-failure behaviour.

Prior to definition of the effects of the shear parameters, all specimens were compacted with the same compactive effort according to ASTM D698 standard using a 10.0 cm diameter by 15.0cm wide mould. The moisture content was determined by oven (ELE 13578) drying.

Sample Preparation

Prior to laboratory testing the lime-iron sludge and soil were dried at 105^0C and then pulverized in a mortar and pestle. The specimens were left in the laboratory for 24 hours to attain equilibrium moisture content, which was found to approximate 12%. The moisture content was verified periodically.

Results and Discussion

The Effect of Lime-iron Sludge on the Index Properties of Inorganic Clay

The index properties of the soil and lime-iron sludge determined according to ASTM D4318 are summarized in Tables 1 and 2 respectively.

TABLE 1 INDEX PROPERTIES OF SOIL

Characteristics	
Soil Type	Inorganic clay of medium plasticity
Liquid Limit	41.40
Plastic Limit	28.24
Plasticity Index	13.16

TABLE 2 INDEX PROPERTIES OF LIME-IRON SLUDGE

Characteristics	
Soil Type	Inorganic silt of low plasticity
Liquid Limit	66.00
Plastic Limit	53.00
Plasticity Index	13.00

Modified specimens were prepared using soil and 3% lime-iron sludge. The index properties of modified specimens determined according to ASTM4318 are

summarized in Table 3. Experimental data indicated that inclusion of lime-iron sludge had a significant effect on liquid limit and plasticity. An increase of 17% in liquid limit together with an increase in plasticity of 43% was obtained. This change in properties may increase the degree to which the material can be moulded or reworked to cause permanent deformation before rupture. A marginal 4% increase in plastic limit was obtained indicating that inclusion of lime-iron sludge has little effect on the dryness of the material.

TABLE 3 INDEX PROPERTIES OF MODIFIED SPECIMENS

Characteristics	
Soil Type	Inorganic clay of medium plasticity
Liquid Limit	48.25
Plastic Limit	29.37
Plasticity Index	18.88

The Effect of Moisture Content on the Shear Stress of Modified soil

The optimum moisture content, that is, the moisture content that leads to the maximum soil density under the particular test conditions was determined by varying the moisture content as well as the percentage addition of lime-iron sludge. The percentage lime-iron sludge was varied between 0% and 10% at a normal stress of 6.38 kN/m². Figure 1 shows the shear stress values obtained when the moisture content was varied between 10% and 30% of the dry weight of modified and unmodified specimens. The results indicated that the increment in the concentration of lime-iron sludge in the soil matrix increased both the shear stress and optimum moisture content.

For unmodified specimens the optimum moisture content was found to be 18%. Modified specimens prepared with 3% lime-iron sludge produced an optimum moisture content of 20%. From Figure 1 it is also observed that a 5% change in moisture content above or below the optimum value results in a significant change in shear stress. At low moisture content a reduced value of shear stress was recorded which may have been due to a decrease in density and thus the need for an increased compactive effort. On the other hand, excessive volumes of water within the soil matrix may have resulted in reduced interlocking and bonding of particles. Hence the soil expanded its volume and the density of the soil particles as well as the shear stress decreased.

By connecting the peak on each curve, a line of optimum moisture content is drawn which enables the determination of optimum moisture content for any lime-iron sludge concentration between 0 and 10%.

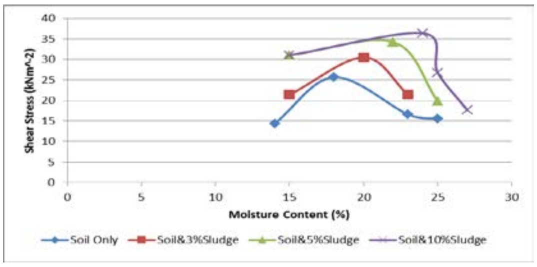

FIG. 1 EFFECT OF MOISTURE CONTENT ON THE SHEAR STRESS OF INORGANIC CLAY FOR DIFFERENT LIME-IRON SLUDGE CONCENTRATIONS

The Effect of Lime-iron Sludge Addition on the Stress-strain Curves of Modified Soil

Figure 2 shows the stress-strain curves obtained when the added amount of lime-iron sludge was varied between 0% and 15% at a normal stress of 6.38 kN/m².

The effect of lime-iron sludge addition at constant compaction showed that the shape of the stress-strain curves differed significantly to that of unmodified specimens. Unmodified soil showed a well defined curve with increasing shear resistance with shear displacement until a constant value was reached. No peak shear stress was obtained over the range of displacement tested. A peak stress was obtained for each sample containing lime-iron sludge, which reduced with continued shearing until the residual stress was reached. A ductile shear interface in which the specimens continue to deform after reaching its peak stress was observed.

Rise in lime-iron sludge concentration between 0% and 10% resulted in an increase in stiffness (i.e., the rate of mobilization of strength with displacement), peak stress and residual stress. As shown in figure 2 the shear stress of the unmodified soil specimens was 25.675 kNm-3. Addition of 3% lime-iron sludge resulted in the formation of a peak stress, 20% beyond unmodified soil stress. The residual stress was 8% beyond that of the unmodified soil. A maximum of 40% increase in peak stress was obtained for modified specimens containing 10% lime-iron sludge.

At 15% lime-iron sludge addition the stress-strain curve initially fell below that of unmodified soil indicating a possible reduction in stiffness. However this modified sample subsequently displayed a gradual increase in residual stress over that of the other specimens tested. This increase may be the result of particle reorientation at the failure surface or changes in the volume of material within the shear

zone.

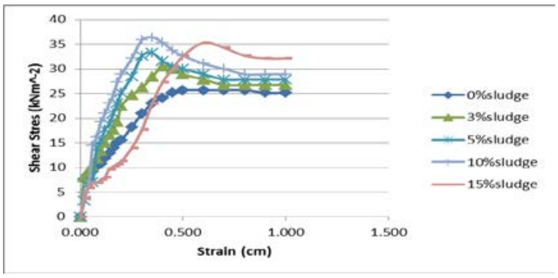

FIG. 2 EFFECT OF VARYING LIME-IRON SLUDGE CONCENTRATIONS ON THE STRESS-STRAIN CURVES AT OPTIMUM MOISTURE CONTENT

The Effect of Lime-iron Sludge on the Failure Envelopes Modified Soil

The Mohr-Coulomb failure envelopes for unmodified and modified specimens at varying normal stresses are presented in Figure 3. Modified specimens were prepared by varying the addition of lime-iron sludge between 0% and 10% and blending at the respective optimum moisture content. As shown in Figure 3, the shear stress increased linearly as the normal load was increased for both modified and unmodified specimens. Under increasing normal stress, soil particles tend to become denser and closer to lime-iron sludge particles thus resulting in greater shear resistance. The failure envelop appears to be linear for normal stresses of 5.10 kN/m^2, 6.38 kN/m^2 and 7.66 kN/m^2.

The results as presented in Figure 3 also indicated that inclusion of lime-iron sludge in soil specimens had minimal effect on its friction angle, which is indicated by the relatively parallel relationship of modified specimens. The friction angles were maintained at 59° for increasing concentrations of lime-iron sludge with the exception of specimens containing 2% lime-iron sludge. This specimen was deviated slightly producing a friction angle of 56°. The variation however may have been due to experimental error.

The inclusion of lime-iron sludge in soil specimens had a significant influence on the development of cohesion (Figure 4). The addition of 2% lime-iron sludge resulted in a 61% increase in both shear stress and cohesion. While the addition of 3% lime-iron sludge increased the cohesion and shear stress by 155%. Increasing the lime-iron sludge concentration beyond 3% resulted in only a marginal increment in cohesion. Thus, 3% lime-iron sludge was selected as the optimum dosage. This observed improvement in the cohesion intercept may have resulted from the developed anchorage forces and interlocking of soil particles.

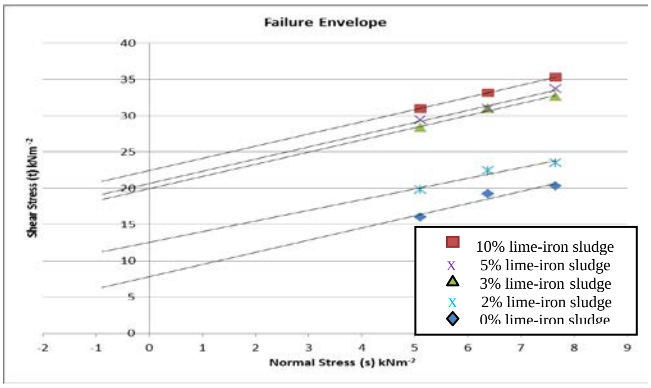

FIG. 3 FAILURE ENVELOPES OF UNMODIFIED AND MODIFIED SOIL AT OPTIMUM MOISTURE CONTENT

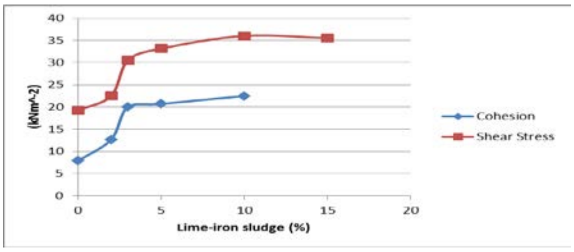

FIG. 4 EFFECT OF LIME-IRON SLUDGE ON THE SHEAR STRESS AND COHESION OF AN INORGANIC CLAY

The Effect of Normal Stress on the Shear Stress of Modified Soil

The effect of normal stress was investigated using specimens prepared at an optimum lime-iron sludge concentration of 3% and an optimum moisture content of 20%. The normal stresses were 5.10 kN/m^2, 6.38 kN/m^2 and 7.66 kN/m^2. The shear stress vs. horizontal displacement curves obtained for unmodified and modified specimens are presented in Figure 5.

A significant increase in initial steepness of curves was observed for all modified specimens when compared to unmodified specimens. This increase indicated that the inclusion of lime-iron sludge resulted in rise in the sample stiffness regardless of the normal stress applied. Mobilized strength increased gradually with increasing normal stress for both modified and unmodified specimens. This was illustrated by the leftward shift of the curves as the normal stress was increased.

There was no observed peak stress over the range of normal stress tested for unmodified specimens. A clear peak stress was obtained for each sample containing 3% lime-iron sludge, which reduced with continued shearing until the residual stress was reached. An increase in both peak stress and residual stress was obtained as the normal stress was increased. There was an approximate 10% increment in peak stress as the normal stress was increased from 5.10 kN/m^2 to 6.38 kN/m^2 and from 6.38 kN/m^2 to 7.66

kN/m², resulting in 20% increase in residual stress and an approximate 10% increase in residual stress, respectively. This change in peak stress and residual stress may have resulted due to an increase in the number of contact points between particles and a subsequent increase in particle resistance.

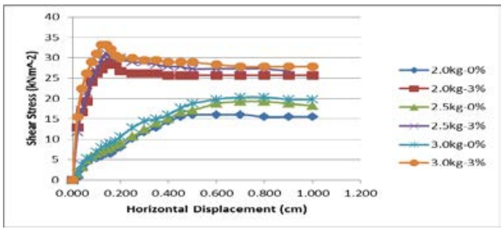

FIG. 5 STRESS VS. HORIZONTAL DISPLACEMENT CURVES FOR UNMODIFIED AND MODIFIED SOIL WITH 3% LIME-IRON SLUDGE AT VARYING NORMAL LOADS

Conclusions

This study was undertaken to investigate the shear behaviour of modified and unmodified clay to determine the potential of using lime-iron sludge as a soil modifier. The effects of lime-iron sludge concentration, moisture content and vertical normal stresses were examined. Based on the output of the research the following conclusions may be drawn:

- Compared to unmodified soil, modified specimens showed increment in shear stress with increasing concentration of lime-iron sludge within the range from 2 to 15%.
- The optimum lime-iron sludge concentration was found to be 3% with a corresponding optimum moisture content of 20%.
- The inclusion of 3% lime-iron sludge resulted in an 8% increase in residual stress over that of unmodified specimens. Further, modified specimens exhibited the development of a peak stress for all values of applied normal load. Addition of 3% lime-iron sludge resulted in the formation of a peak stress, approximately 20% beyond unmodified soil stress.
- The inclusion of lime-iron sludge as a soil modifier resulted in a significant improvement on the cohesion intercept. At optimum lime-iron sludge concentration 3% there was 155% increase in cohesion. However no noticeable change was observed with regard to the friction angles of modified specimens.

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